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RESEARCH PAPER

Environmental spatial assessment at ranch scale: a tool for optimizing livestock management in Argentine forests

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Abstract

Question: Effective environmental management depends on accurate and efficient assessments of ecological conditions. This study introduces a method that combines remote sensing with a Rapid Assessment Method (RAM) to evaluate the environmental status of land units at the ranch scale. We ask whether this integrated approach can generate spatially explicit information to support the implementation and monitoring of sustainable livestock grazing in native forests. **Study area:** The study was conducted in three livestock ranches in Argentina. These ranches encompass heterogeneous landscapes characterized by varying soil types, vegetation cover, and topographic features that influence ecological conditions. **Methods:** Remote sensing imagery was used to delineate Ecological Sites (ESi) based on bio-geomorphic attributes such as soil, topography, and vegetation. These spatial units guided field sampling, where RAM was applied to assess environmental indicators. Field data were integrated into an Environmental Health Index (EHI), summarizing the ecological status of each ESi. Ordinary kriging interpolated EHI values across the landscape, enabling spatial visualization of environmental health patterns and spatial variability. **Results:** Mapping of EHI values showed that most land units exhibited intermediate to high environmental health, suggesting generally favorable ecological conditions across the ranches. However, some areas had low EHI values associated with signs of disturbance or degradation, including fire, flooding, invasive species, or overgrazing. **Conclusions:** The integration of remote sensing with RAM provided a detailed overview of ecological conditions at the ranch scale. The results can guide more focused and efficient fieldwork in areas requiring closer monitoring due to potential environmental degradation or changes linked to livestock management. This approach supports the implementation and evaluation of sustainable grazing management in native forests, offering a robust, scalable tool for environmental assessment. Additionally, by optimizing the allocation of sampling effort, it enables more informed decision-making to maintain and enhance ecological health in these production systems.

Taxonomic reference: Anton and Zuloaga (2023).

Abbreviations: EHI = environmental health index; ESi = ecological site; RAM = rapid assessment methodology; MBGI = silvo pastoral or forest management with integrated livestock.

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Keywords

Argentina, environmental degradation, environmental health index (EHI), integrated forest and livestock management, remote sensing, vegetation assessment

Introduction

Livestock production in native forest ecosystems presents the challenge of minimizing ecological degradation while maximizing conservation and improving production efficiency through sustainable management practices (Mori et al. 2017; Acharya et al. 2019). Considering global priorities for forest conservation and reduction of greenhouse emissions from livestock production, it is crucial to promote the implementation of sustainable forest management practices that integrate livestock production (Nellemann et al. 2009; Papanastasis 2009; Calle et al. 2012; Bonilla-Cedrez et al. 2023). A fundamental step in sustainable livestock management is the identification of distinct environmental units at the ranch scale, which enables more precise planning and decision-making (Peri et al. 2021). However, there is a lack of spatially explicit tools to support the implementation of livestock-forestry management strategies based on environmental data (Loiseau et al. 2012; Guerra et al. 2016).

The use of remote sensing images for identifying homogeneous environments is a highly promising tool that facilitates, expedites, and reduces the cost of environmental descriptions of livestock ranches, regardless of their size (Pettorelli et al. 2014; Maynard and Karl 2017; Rhodes et al. 2022). The Ecological Site (Esi) framework has its basis in remote sensing imagery, which is used for classifying and mapping ecosystems (Creque et al. 1999; Bestelmeyer et al. 2009; National Ecological Site Handbook 2019). Ecological Sites are landscape units that share similar characteristics in soil, topography, hydrology, climate, and potential vegetation characteristics, and are expected to respond similarly to disturbances and management practices (Bestelmeyer et al. 2017). Each Ecological Site is linked to the Vegetation States, which represent the structural and compositional condition of vegetation at a particular time. In some cases, it is possible to determine a Reference State among various vegetation conditions, reflecting the potential ecological state of the ecosystem, without significant human alteration (Bestelmeyer et al. 2017).

The Ecological Sites approach helps ground management decisions with current environmental data, thereby improving the implementation of livestock and forest management measures within a sustainability framework. For example, in the north of Patagonia (Argentina), the use of an open-access tool to determine Ecological Sites within a ranch (Ecological Sites viewer; Varela et al. 2022) constituted the starting point for implementing management schemes such as silvo pastoral or forest management with integrated livestock (MBGI, for its acronym in Spanish; Peri et al. 2021). Additionally, it offers the advantage of maximizing the use of human, time, and financial resources, because it helps to conduct field sampling more effectively. However, the approach is based on remote sensing images, without the possibility of knowing the actual environmental status of specific sites. In this context, Rapid Assessment Methods (RAMs) emerge as a powerful complementary tool to Ecological Sites.

Rapid Assessment Methodologies (RAMs) have been developed as effective tools for evaluating and quantifying several environmental attributes in both natural and human-modified areas (Sayre et al. 2000; Groot et al. 2002; Fennessy et al. 2007; Kangas et al. 2019). These methodologies allow a rapid assessment of biodiversity, vegetation structure, soil quality, and anthropogenic impacts, such as livestock grazing and natural vegetation modification, thus supporting real-time decision-making for management and conservation. In landscapes where forests and livestock coexist, RAMs are particularly valuable for addressing the complex ecological interactions and potential consequences of land-use decisions (Fennessy et al. 2007). Thus, RAMs are useful for elucidating the dynamic relationships between natural resources and human activities, contributing to a deeper understanding of ecosystem health and resilience rapidly and cost-effectively (Fennessy et al. 2007). Finally, a widely used concept in ecosystem assessment and monitoring is 'environmental health' (Rapport 1998), which refers to the degree to which soil integrity, vegetation structure and composition, and ecological processes of the ecosystem are maintained (Gewin 2002; Pellant et al. 2020). The related term 'ecosystem health' describes the overall status of an ecosystem, which can vary due to disturbances and other environmental factors (Rapport 1998; Lackey 2001). Therefore, the periodic monitoring of the environmental health enables decision-makers to implement timely and targeted management interventions, particularly within an adaptive management framework (Lindenmayer and Likens 2009).

In Argentina, the Forest Management with Integrated Livestock approach (MBGI for its Spanish acronym, Manejo de Bosques con Ganadería Integrada) is a technical framework that promotes the sustainable management of forestry, livestock, forage, environmental, and socio-economic components within a ranch, articulated into a strategic and actionable plan (Carranza et al. 2015; Navall et al. 2016; Peri et al. 2018). This framework requires monitoring multiple components within an adaptive management scheme, with regular assessments to ensure that planning aligns with sustainability objectives. The implementation of MBGI in Argentina is currently

standardized for specific vegetation types, such as multispecies forests in the Chaco region (Carranza et al. 2019) and monospecific *Nothofagus antarctica* (ñire) forests in Patagonia (Peri et al. 2021). However, management plans in other regions should consider a wider range of forest ecosystems, as livestock raising occurs in multiple forest types, each with unique environmental characteristics and regeneration dynamics (Peri and Raffaele 2016). Therefore, standardized tools are necessary to easily identify and categorize forest types in the field, as an initial step towards implementing MBGI plans on a national scale. Currently, managers have access to sustainability indicators guides covering socio-economic, productive, and environmental dimensions for two ecoregions in Argentina: the Parque Chaqueño (Carranza et al. 2019) and Patagonia (Peri et al. 2021). While these guides provide valuable support for managers, the proposed field methodologies for assessing environmental indicators face significant challenges due to the high effort required, stemming from the complexity and heterogeneity of forested ecosystems used for livestock production. To address this challenge, there is a need for economic and simplified methodologies to evaluate and establish baseline environmental conditions.

The objectives of this study were to i) define the Ecological Sites for each livestock ranch based on remote sensing techniques (Alaggia et al. 2020; Varela et al. 2022), ii) apply a field-based *ad hoc* spatially integrated Rapid Assessment Method (Varela et al. 2023) in each ranch, iii) estimate, integrate, and map an Environmental Health Index (EHI) to guide sampling and livestock management for each Ecological Site at the ranch level. Ecosystem health can be affected by disturbances such as fire, flooding, drought, extinctions, invasive species, climate change, chemical spills, or agricultural production activities, including livestock raising, farming, or logging (Rapport 1998; Lackey 2001). Therefore, we integrate environmental indicators evaluated with RAM and related to disturbance factors and stressors, both in terms of their presence (direct or indirect evidence of the disturbance, such as overgrazing, invasive species, trampling, and browsing) and their impact on the system (e.g., loss of forest cover, reduced or absent tree regeneration, soil erosion) into an EHI. We expect that 1) the integration of remote sensing-based Ecological Site classification with field-based Rapid Assessment Methodologies (RAMs) will improve the spatial precision and effectiveness of environmental health assessments in livestock-forest systems and, 2) the Environmental Health Index (EHI), derived from RAM indicators, will provide a reliable tool for evaluating ecosystem integrity, facilitating adaptive management in livestock-forestry landscapes. In this way, we aim to provide a tool that facilitates a comprehensive characterization of the environmental status of livestock-raising ranches in terms of degradation of ecosystem identity and integrity, thereby contributing with evidence-based decisions in order to balance livestock production and forest conservation.

Study area

The study was conducted on three livestock ranches located in the Argentine provinces of Entre Ríos, Neuquén, and Río Negro (Figure 1). The ranches vary in size from 82 to 12,450 ha and based on their geographical location, incorporate multiple forest types. The main economic activity on these ranches is livestock production, mainly cattle raising within native forests. However, these ranches currently lack a systematic indicator scheme to monitor the performance of the ecosystem in response to sustainable livestock management practices, such as the MBGI framework.

The ranch in Entre Ríos Province, El Carayá, is a 12,450-ha property (-30.631549°S, -58.783734°W, Figure 1A) where the average annual rainfall ranges between 1,000- and 1,200-mm. The predominant vegetation in the uplands consists of xerophytic forests dominated by "algarrobos" (mainly ñandubay, *Neltuma affinis* and black carob, *Neltuma nigra*) and "espinillo" (*Vachellia caven*). In the lowlands and along watercourses, hygrophilous forests are present, exhibiting transitional characteristics between the Espinal and Paranaense ecoregions (Morello et al. 2012). Additionally, 2.4% of the ranch area (approximately 2,048 ha) is dedicated to rainfed crops (mainly corn and sorghum), annual pastures, and rice (Sabattini and Sabattini 2019; Reales et al. 2021).

The main activity at El Carayá is cattle raising (Aberdeen Angus breed, average stocking rate: 0.5 AU ha^{-1}, rotational grazing), which serves as the initial link in the meat supply chain for its owner, a livestock and dairy enterprise (Las Taperitas S.A.). Beyond its commercial objectives, the ranch also contributes to the conservation of native forests of the Entre Ríos Espinal, with 10,400 ha designated as a Natural Protected Area in the form of a Multiple-Use Reserve (Sabattini and Sabattini 2019; Reales et al. 2021). Furthermore, aligned with the corporate social responsibility policy of Las Taperitas S.A., the ranch administration actively promotes innovation and continuous improvement in livestock production practices in northern Entre Ríos.

The ranch in Neuquén Province, Tres Lagos, covers 22,224 ha (-40.50075°S, -71.33449°W, Figure 1B) and is located within the area influenced by the Lanín and Nahuel Huapi National Parks. It is part of the Andean Patagonian Biosphere Reserve, which is shared with Chile (Beha Ambiental 2015). The area under livestock use (Hereford breed, average stocking rate: 0.04 AU ha^{-1}, rotational grazing), corresponds to a glaciofluvial valley situated between two lakes, covering 2,984 ha (Figure 1B). The valley bottom is characterized by shrubland, with "ñire" (*Nothofagus antarctica*) as dominant species, accompanied by *Berberis buxifolia*, *Berberis darwinii*, *Senecio filaginoides*, and grasses such as *Festuca pallescens*, *Pappostipa humilis*, *Poa pratensis*, and *Holcus lanatus*. On the surrounding slopes, the vegetation gradually transitions into forests dominated by Andean cypress (*Austrocedrus chilensis*), coihue (*Nothofagus dombeyi*), and lenga (*Nothofagus pumilio*) at higher elevations. Additional to livestock management, specific areas are designated for recreational activities such as camping, fishing, hunting,

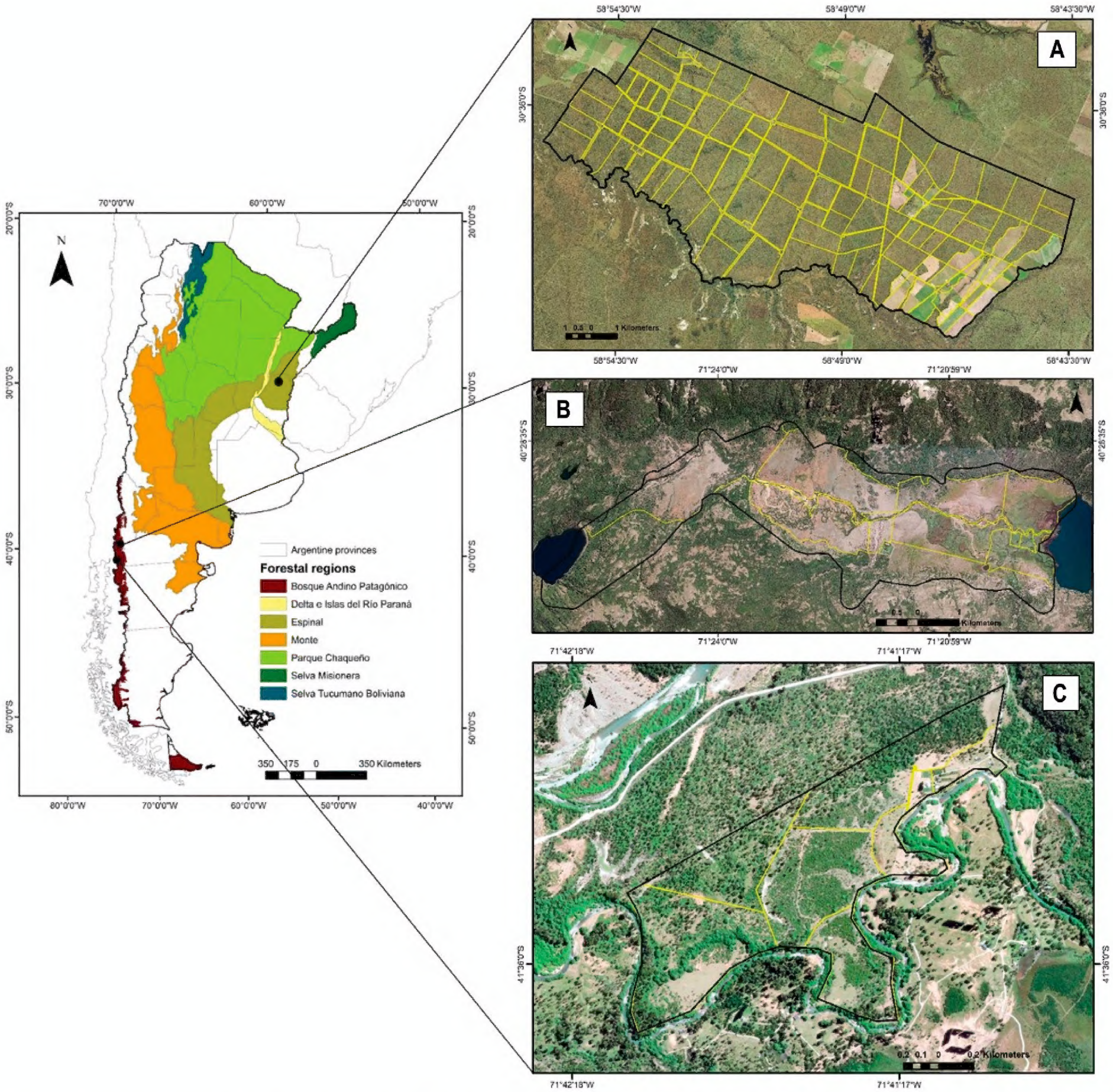

Figure 1. Location of the studied ranches in relation to Argentinean Forestal Regions and satellite images showing the surface detail of each: A) El Carayá ranch, Entre Ríos province, B) Tres Lagos ranch, Neuquén province, and C) El Jabalí ranch, Rio Negro province. Yellow lines in the satellite images correspond to paddock limits.

and horseback riding. Some areas of the ranch show elevated levels of environmental degradation due to invasive wildlife species, including red deer (*Cervus elaphus*), European rabbit (*Oryctolagus cuniculus*), and wild boar (*Sus scrofa*), which often overlap with livestock grazing areas (Borrelli et al. 2023). The average annual rainfall in this region is 1,200 mm (Bianchi et al. 2016).

Finally, the ranch in Río Negro Province, El Jabalí, is an 82-ha property dedicated to agriculture and livestock production (Hereford breed, average stocking rate: 0.52 AU ha^{-1}, rotational grazing), located approximately 90 km from San Carlos de Bariloche city (-41.59224°S, -71.68382°W, Figure 1C). The native forest on the ranch includes tree species such as "coihue", "ñire", "maitén" (*Maitenus boaria*), and Andean cypress. Additional smaller tree species include "chin chin" (*Azara microphylla*), "maqui" (*Aristotelia chilensis*), and the southern margin of the property is dominated by colihue cane, which is heavily browsed, and shrubs like "chacay" (*Discaria chacaye*) and "pañil" (*Buddleja globosa*). Forage species include "retamo" (*Diostea juncea*), along with tall grasses such as colihue cane (*Chusquea culeou*), ovillo grass (*Dactylis glomerata*), clovers (*Trifolium* spp.), and honey grass (*Holcus lanatus*). The landscape is characterized by gentle slopes and primarily flat riverbeds, with sandy loam soils that have surface clay in some areas. These soils are shallow and easily erodible, with vegetation roots playing a critical role in stabilization and protection. The average annual rainfall is 1,800 mm. Historically, El Jabalí has been used for low-density livestock production and the exploitation of

native forest products, without planning based on sustainable use. Currently, the ranch is highly diversified, with activities including cattle, pig, poultry, and sheep production (for lamb), horticulture, fine fruit cultivation (raspberry), and cereal farming (wheat). Wool production is not a primary activity and is mainly for local consumption or sale. One of the main limitations of livestock production is the invasion of woody shrub species, such as rosehip (*Rosa eglanteria*) and blackberry (*Rubus ulmifolius*), which gradually reduces forage availability for livestock.

Methods

Delimitation of ecological sites (ESi) at the ranch level

The first step in designing a Management Plan for MBGI is to identify homogeneous environmental units within the ranch, referred to as Ecological Sites (ESi; Bestelmeyer et al. 2017). At El Carayá ranch, we delimited the ESi using topography and vegetation data, analyzed with the Geographical Information System software ArcMap 10.7.1 (ESRI, Redlands, California, USA). This characterization was complemented by previous characterizations of soils (based on information from INTA Plan Mapa de Suelos 1986) and vegetation (Sabattini and Sabattini 2019; Reales et al. 2021).

At the El Jabalí and Tres Lagos ranches, we employed an early version of the ESi viewer developed by Trinco et al. (2024, https://fabiotrinco.users.earthengine.app/view/sitios-ecologicos-patagonia-escala-predial) in Google Earth Engine App. This tool uses a random forest model to determine the ESi and reference states (RS) in areas with low mixed forests (post-disturbance recovery communities) in Northern Patagonia. The classifications are based on initial layers of mean annual precipitation and temperature, topographic variables (altitude, slope, and aspect), meadow probabilities, and distance to rivers. Mean annual precipitation and temperature data were derived from models proposed by Bianchi et al. (2016) and Bianchi and Cravero (2010), respectively. Altitude, slope, and aspect were determined using models by NASA JPL (2020), while meadow probabilities were calculated using a model by Navarro et al. (2022). Distance to rivers was estimated based on models by Grill et al. (2019) and Lehner et al. (2008). Polygons representing barren lands, herbaceous/subshrubs, wetlands, and various forest types were extracted from the most recent classification of native forests for Neuquén, Río Negro, and Chubut (CIEFAP-MAyDS 2016), using their descriptive characteristics as proxy variables for the reference states of each forest type (Varela et al. 2022).

Rapid Assessment Method (RAM)

We applied the Rapid Assessment Method (RAM) proposed by Varela et al. (2023), which emphasizes increased replication of sampling units across space to better capture spatial heterogeneity at the ranch level. This approach overcomes the limitation of previous MBGI guidelines, which required one sampling site per 500 hectares and proved challenging for smaller ranches (Carranza et al. 2019; Peri et al. 2021), by enabling more flexible sampling methodology and enhancing the ability to capture the spatial heterogeneity of complex systems. Additionally, this method recommends qualitative field observations to expedite the assessment of each sampling unit. We gridded the ranch surface using a regular pattern of points, where the spacing between points was adjusted according to the ranch's total area and vegetation diversity. The minimum distance between consecutive points was set at 250 meters. At each point, we established circular plots with a diameter of 20–25 m, and we filled out a simple survey form that included qualitative and quantitative indicators of the forest's environmental status.

We described the ecological condition of forests in each sampling plot by assessing key environmental features, including the predominant vegetation type (e.g., forests of "ñandubay", espinillo", "ñire", "coihue", "Andean cypress", riparian forest, steppe, etc.); herbaceous cover as a proxy for "forage availability"; the presence of indicator species of specific vegetation types; and ecological processes, such as loss of tree cover, shrub encroachment, and invasion by exotic species (see Rusch and Varela 2019 for more details). We also considered management practices (e.g., grazing, logging) and signs of exotic wildlife presence, such as European rabbit (*Oryctolagus cuniculus*) and European hare (*Lepus europaeus*) (Suppl. material 1). We also qualitatively estimated the intensity of habitat use by exotic wildlife using three indicators: footprints, feces, and direct observations.

Additionally, we evaluated signs and extent of degradation processes, including soil erosion (assessed through physical crusts and mulch cover) and overgrazing (associated with exotic wildlife presence and changes in herbaceous cover). Finally, we included indicators of forest structure and regeneration processes, such as upper canopy cover, abundance of native tree renewal (in the case of El Carayá ranch), tree height, tree density, and relative regeneration rate (in Patagonian ranches, *sensu* Peri et al. 2021) (Suppl. material 1). In the Patagonian ranches, we also conducted a simplified forest inventory in circular plots. These inventories allowed us to characterize both advanced and early-stage tree regeneration at each circular plot (see Varela et al. 2023 for more details).

Estimation of an Environmental Health Index (EHI)

We estimated an Environmental Health Index (EHI) by summing the values recorded in each RAM sampling plot. This index was designed to represent a gradient of environmental status, ranging from "worst" (lowest values = 0) to "best" (highest value = 1) at each sampling plot. To facilitate the interpretation of the index, those variables

with a value of "0" (absence) that indicated a good environmental condition (e.g., absence of exotic or invasive species) were switched to "1" to get the desired significance in the summary index (Suppl. material 1). Similarly, quali-quantitative variables ranging from 0 to 3 or 4, where lower values indicated better environmental quality (e.g., abundance of invasive trees, coverage of invasive herbaceous species), were inverted to ensure the summary index accurately reflected environmental significance.

Finally, to generate the EHI, the values of the selected variables (23 in Entre Ríos and 24 in Patagonia; Suppl. material 1) were then summed and standardized using the min-max normalization method. The Min-Max Method, as described by Sharaff and Sinha (2021) and Singh et al. (2009), is a data analysis technique commonly used in multi-criteria studies (Nardo et al. 2005). This method is based on identifying the extreme values (minimum and maximum) of an interest variable within a dataset, and transforming the original values to a common scale (e.g., between 0 and 1) using the following formula:

$$X' = X - X_{min} \,/\, X_{max} - X_{min}$$

Where X' is the normalized value of the variable; X is the original value of the variable of interest; X_{min} is the minimum value of the evaluated criterion; X_{max} is the maximum value of the evaluated criterion. This standardization captured differences among sampling units on a consistent scale. The maximum (1) is established as the highest value of each criterion, indicating the optimal or desired level.

To allow a straightforward relationship between each recorded indicator and the corresponding ecosystem component or process we present the percentage of total plots at each site grouped in 3 categories: Soil, Vegetation and Threats/Degradation processes (Suppl. material 1).

Mapping of the Environmental Health Index (EHI)

We performed statistical analyses of the EHI data using the Geostatistical Analyst extension in ArcMap 10.7.1® (ESRI, Redlands, California, USA) to assess the suitability of the data for spatial interpolation. We examined histograms and skewness measures to identify outliers and quantile-quantile (QQ) plots were used to compare the data distribution with a standard normal distribution. The Trend Analysis tool was additionally used to identify any trends within the ESi data, which were removed if detected. Additionally, "no search direction" semi-variogram/covariance clouds were generated to examine spatial autocorrelation (Munyati and Sinthumule 2021).

We then mapped the EHI using ordinary kriging, a geostatistical method for spatial data interpolation. Kriging methods account for the spatial correlation of observations during data processing and incorporate both the distribution and spatial variability of the data (Mendez and Calvo-Valverde 2016). These methods have demonstrated better performance than deterministic approaches, such as Thiessen polygons, simple regression, and Inverse Distance Weighting (IDW), which are commonly applied in environmental sciences (Arétouyap et al. 2016; da Silva Charles et al. 2022). In particular, ordinary kriging is the most widely used method for interpolating environmental attributes (van Groenigen 2000). As a result, we applied ordinary kriging to fit a variogram model, using the distance between two points to predict the semi-variance of the EHI. This method minimizes prediction errors while maximizing spatial variation in the data (Akkala et al. 2010; Giraldo et al. 2011; Oliver and Webster 2015).

The inter-site semi-variances of data from a measured network were utilized to create a system of linear equations, which predicts the semi-variance at an unmeasured site as a linear sum of the semi-variances between all observed sites (Asa et al. 2011; Farmer 2016). An empirical variogram, $\gamma(h)$, is defined as half of the mean of the squared differences between two observations separated by a distance vector (h) (Nouck et al. 2013):

$$\gamma(h) = \frac{1}{2N(h)} \sum_{i-1}^{N(h)} [z(x_i) - z(x_i + h)]^2$$

Where $\gamma(h)$ is the semi-variance at distance h, $N(h)$ is the number of pairs of points separated by distance h, and z (x_i) and z $(x_i + h)$ are the values of the environmental integrity index at two locations separated by distance h.

To predict the EHI for each ranch, we randomly divided the EHI sampling points into two sets: 70% for model calibration and 30% for independent model validation. After analyzing the performance of the semi-variogram models and their parameters, we generated final interpolation predictions for the EHI for the three ranches by comparing five common semi-variogram models: stable, circular, spherical, exponential, and Gaussian. Transformation of the sample data to logarithms is necessary if skewness >1 (Oliver and Webster 2014).

The models' performance was evaluated based on the accuracy of their predictions, using the following cross-validation statistical criteria (Kambhammettu et al. 2011; Arétouyap et al. 2016): (1) Predictions should be unbiased, as indicated by a mean error (ME) close to 0; (2) Predictions should not deviate significantly from the observed values, as reflected by a root-mean-square error (RMSE) and mean standard error (MSE) that are as small as possible, and (3) Standard errors should be accurate, demonstrated by a root-mean-square standardized prediction error (RMSSE) close to 1 (Munyati and Sinthumule 2021).

Finally, the spatial distribution of the EHI was obtained using the selected interpolation model for each studied ranch at a 10-meter resolution. The validation analysis, performed with the remaining 30% of the dataset, was conducted in R software (version 4.0.2) using the *knitr* package (Xie et al. 2024). The spatial resolution was chosen to capture landscape details while maintaining analytical integrity, allowing for an adequate representation of land use variations and environmental characteristics.

Results

Ecological site descriptions across ranches

In El Carayá, a total of six ecological sites (ESi) were identified regarding soil type, slope, and vegetation (Figure 2A, Table 1). The predominant ESi was the "ñandubay" and "espinillo" xerophytic forest, covering 62% of the area (7013 ha). The "ñandubay" and "espinillo" xerophytic forest was situated in highland and midland zones, featuring very gently undulating slopes, high plateaus, and vertisol soils. Additionally, we identified the midland xerophytic forest with palms located in the midland areas with saline vertisols (>10% sodium saturation) and covered 10% of the total area (1165 ha). Besides "ñandubay" and "espinillo", this site also included characteristic species such as "quebracho blanco" (*Aspidosperma quebracho-blanco*) and caranday palm (*Trithrinax campestris*). The ESi corresponding to hygrophilous forests in streams and transition hygrophilous forests were identified in internal hygrophilous forests on poorly drained alfisol soils, with varying degrees of transition between floodable valleys and hills. These ESi also included typical hygrophilous tree species such as "guayabo colorado" (*Myrcianthes cisplatensis*), "blanquillo" (*Sebastiania commersoniana*), "coronillo" (*Scutia buxifolia*), and "anacahuita" (*Blepharocalix tweedii*). These ESi covered 17% of the ranch area (8%, 920 ha; and 9%, 969 ha, respectively, Figure 2A, Table 1). Lastly, the ESi corresponding to hygrophilous lowland forest (Figure 2A), located at the lowest topographical elevation on the ranch, featured poorly evolved soils associated with water bodies. Unlike other ESi, the vegetation in this site was mainly associated with the Paraná forest ecoregion and included species such as "sarandí blanco" (*Phyllanthus sellowianus*), "yuquerí negro" (*Senegalia praecox*), and "viraró" (*Ruprechtia laxiflora*). This ESi covered 11% of the ranch area (1251 ha), with 250 ha excluded from livestock production due to its proximity to a major watercourse along the southern boundary of the ranch (Figure 2A).

In Tres Lagos, a total of eight ESi were identified (Figure 2B, Table 1). The herbaceous/subshrub ESi (36.8%, 1,097 ha) was characterized by low-growing vegetation. The "ñire" forest ESi (24.6%, 733 ha) was located in both moist and dry environments (peat bogs and wetlands, and steppes, respectively). "Ñire" forests were located on average 586 m from rivers, on slopes with an average gradient of 44.5 degrees, elevations of around 1066 m a.s.l., and received approximately 1552 mm of average annual precipitation. The Andean cypress forest ESi (17.3%, 516 ha) was typically found on moderate slopes with an aspect of 359°, indicating a northern orientation, and was situated closer to rivers than some other sites.

These forests had an average elevation of about 1066 m a.s.l. and received approximately 1523 mm of annual precipitation. Near the main water body (Lake Filo Huahum, east of the ranch), we identified an ESi with wetlands (locally known as "mallines"; 15.2%, 452 ha, Figure 2B), with an intermediate aspect compared to other regions, situated at intermediate elevations. Wetlands had shorter distances to rivers and moderate slopes. "Coihue" forest ESi (3.8%, 113 ha), was found on moderate slopes with an aspect value of 358.0°, at the lowest average elevation of 1067 m a.s.l., and was located 595 m from rivers. This ESi received the highest annual precipitation of 1600 mm and maintained consistent humidity. The mixed forest ESi (2%, 59 ha) was found on moderate slopes with varying orientations, in well-drained areas. Barren land (0.2%, 6 ha) occured in the valley bottoms, often corresponding to historical riverbeds. Finally, at higher altitudes (average elevation of 1094 m a.s.l.), the "lenga" forest ESi (0.2%, 5 ha) was found on slopes with an aspect value of 177.0°, indicating a southern orientation, situated at the highest elevation with an average distance of 734 m from rivers, and an average slope of 26°. Water bodies accounted for 0.1% (3 ha) of the studied surface in this ranch. The average annual temperature in Tres Lagos ranged from 6.5 to 6.7°C.

In El Jabalí, four ESi were identified (Figure 2C, Table 1). An ESi with wetlands was predominant, covering 43.4% of the area (36 ha). Andean cypress forest and "ñire" forest ESi had similar proportions of ranch area coverage, while mixed forest ESi covered a smaller area (27%, 22 ha; 23%, 18 ha; and 7%, 6 ha, respectively). The distribution of ESi in this ranch was primarily attributed to slope and exposure rather than significant altitudinal gradients. Regarding aspect, Andean cypress forest had the highest average value (173°), followed by "ñire" forest (171°), and wetlands (169°), with standard deviations being similar across these areas. Similarly, Andean cypress forest ESi had the highest average distance to rivers (246 m), followed by wetlands (231 m), and "ñire" forest (159 m). Mean elevations were similar across ESi, with Andean cypress forest slightly higher (451 m a.s.l.), followed by "ñire" forest (449 m a.s.l.), and wetlands ESi (450 m a.s.l.). In terms of slope orientation, all areas showed predominantly positive slopes. "Coihue" forest ESi was characterized by the highest average annual precipitation (1724 mm), followed by "ñire" forest (1700 mm) and wetlands (1702 mm). The probability of humidity was highest in wetlands (0.51), followed by "ñire" forest (0.50) and Andean cypress forest (0.36) ESi. Slope values were highest in Andean cypress forest (2.5), followed by wetlands (2.3) and "ñire" forest (1.9) ESi. Average annual temperatures were similar across all areas, around 7.6°C.

Rapid Assessment Method results across ranches and ecological sites (ESi)

The number of sampling plots varied across ranches, based on the ranch area and the number of ESi. In El Carayá, 92 plots were surveyed, allocated proportionally to each ESi (Figure 2A). This ranged from 7 plots in the hygrophilous lowland forest (8% of the ranch area) to 31 plots in the midland xerophytic forest (with and without palm; 33% of the ranch area, Figure 2A). Most plots (60% or more) were in forests with estimated tree densities ranging from medium to high and tree heights from low to medium (Table 2). Ex-

otic trees were observed in only 2% of the plots, while the presence or absence of native tree and palm species varied with the proportion of sampling plots allocated to each ESi. *Neltuma affinis*, an indicator species of northern Espinal forests, was present in nearly 90% of the plots, whereas other tree species, such as *Aspidosperma quebracho-blanco* and *Butia yatay*, were present in approximately half of the plots or were absent (Table 2). Shrub coverage was generally below 20% (n = 46, 70% of plots), primarily by *Aloysia gratissima*, whereas herbaceous coverage was usually above 20% (n = 76, 84% of plots), with invasive herbaceous species absent from more than half of the plots. Evidence of forest degradation, including soil erosion, dead trees, or fire, was largely absent (>60% of plots), while signs of overgrazing were present in 70% of the plots (Table 2).

In Tres Lagos, 227 plots were surveyed in multiple ESi (Figure 2B), including one plot in "lenga" forest, 145 in "ñire" forests, three in "coihue" forest, 50 in wetlands, and 27 in Andean cypress forest. Forty-eight of the total plots used in this ranch corresponded to forest typologies (primarily "ñire" forest), 27 to barren land ESi, 115 to wet and subhumid steppes dominated by wetlands (Wetlands ESi), and 37 to shrublands in areas of Wetlands and Andean cypress forest ESi. The main variations in plot integrity and/or deterioration were related to grassland condition, the presence or absence of *Chusquea culeou*, *Acaena splendens*, *Rosa eglanteria*, and *Berberis* spp. as indicator species, the presence of wildlife (rabbits, deer) and livestock (cattle, horses), and erosive/disturbance processes such as loss of vegetation cover, shrub encroachment, volcanic ash accumulation, and accumulation of dead woody material (Table 2). Relative regeneration showed more stable and higher values compared to the El Jabalí ranch (see below).

In El Jabalí, 63 plots were surveyed (Figure 2C), with 37 in the "ñire" forest, 15 in the "coihue" forest, and 11 in wetlands. Of these, 29 plots corresponded to forest typologies, 17 to wet steppes, 15 to shrublands, and two to riparian zones. The main variations in plot integrity and/or deterioration were associated with the presence of indicator species (mainly *Rubus ulmifolius*, *Rosa eglanteria*, and *Chusquea culeou*), the presence of cattle and equines, and erosive/disturbance processes, including shrub encroachment, accumulation of dead woody material, browsing, and invasion processes (Table 2).

Environmental Health Index (EHI) results across ranches and ecological sites (ESi)

The five statistical models evaluated for mapping the Environmental Health Index (EHI) at each ranch performed equally well, based on the minimal error component of cross-validation statistics (Suppl. material 2). However, according to the selection criteria (see Mapping of the Environmental Health Index, in the Methodology section), the circular semi-variogram model performed slightly better for the El Carayá and Tres Lagos ranches, while the exponential model showed the best fit for the El Jabalí ranch (Suppl. material 2). Finally, the global accuracy of the final interpolation predictions for the spatial distribution of the EHI showed that the mean squared error (MSE) and root mean squared error (RMSE) were close to zero for all three ranches (0.027 and 0.167 for El Carayá; 0.046 and 0.214 for Tres Lagos; 0.049 and 0.222 for El Jabalí). These results suggest that the interpolation model produced reliable predictions with minimal deviation from the observed data (Suppl. material 3).

In El Carayá, the average EHI value exceeded 0.50 across all ESi, with most of their surface areas exhibiting intermediate to high EHI values (> 0.5) (Table 1, Figure 3A). Specifically, 95% of the highland xerophytic forest had EHI values ranging from 0.44 to 0.67. For the midland xerophytic forest, both with (87%) and without (81%) caranday palm, had EHI values ranging from 0.44 to 0.73. The transition hygrophilous forest showed 67% of its surface with EHI values between 0.57 and 0.73. The hygrophilous forest in streams exhibited the highest proportion of high EHI values, with 90% of its area ranging from 0.44 to 0.77. Similarly, the hygrophilous lowland forests had 81% of their area with EHI values between 0.57 and 0.73. The distribution of degraded and less degraded forests varied across the ranch, with less degraded forests (higher EHI values) predominantly located in the west and central-eastern regions (Figure 3A, darkest colors). Conversely, most degraded forests (lower EHI values) were mainly found in the northeast and southwest regions (Figure 3A, light colors).

In Tres Lagos (Table 1, Figure 3B), as in El Carayá, all ESi exhibited mean average values between 0.49 and 0.55 (Figure 3B). For all ESi considered, except the wetlands, a higher proportion of surface areas had average EHI values ranging from 0.43 to 0.57 (Table 1, Suppl. material 3). For instance, 97% of the barren land showed EHI values between 0.53 and 0.57; 84% of the herbaceous/subshrubs, 88% of the "ñire" forest, 63% of the "coihue" forest, and 50% of the Andean cypress forest had values between 0.43 and 0.57. The wetlands, however, showed a more even distribution of surface areas across different EHI ranges, with 98% of its surface varying between 0.47 and 0.64.

In El Jabalí, all ESi had mean values below 0.45 (Table 1, Figure 3C). Some ESi in this ranch also exhibited large areas with low EHI values. For example, 48% of the "coihue" forest, 54% of the "ñire" forest, and 18% of the mixed forest ESi had values ranging from 0.16 to 0.32. Only the wetlands showed 65% of their surface with EHI values between 0.41 and 0.73 (Table 1, Suppl. material 3).

Discussion

The methodological approaches applied in this study enabled the identification of multiple homogeneous environmental units (ESi) at the ranch scale with a high degree of precision. By integrating remote sensing data with field evaluations – such as the Rapid Assessment Method (RAM) – we obtained a spatially explicit representation of environmental health conditions within each ESi, based on soil characteristics, vegetation, and degradation

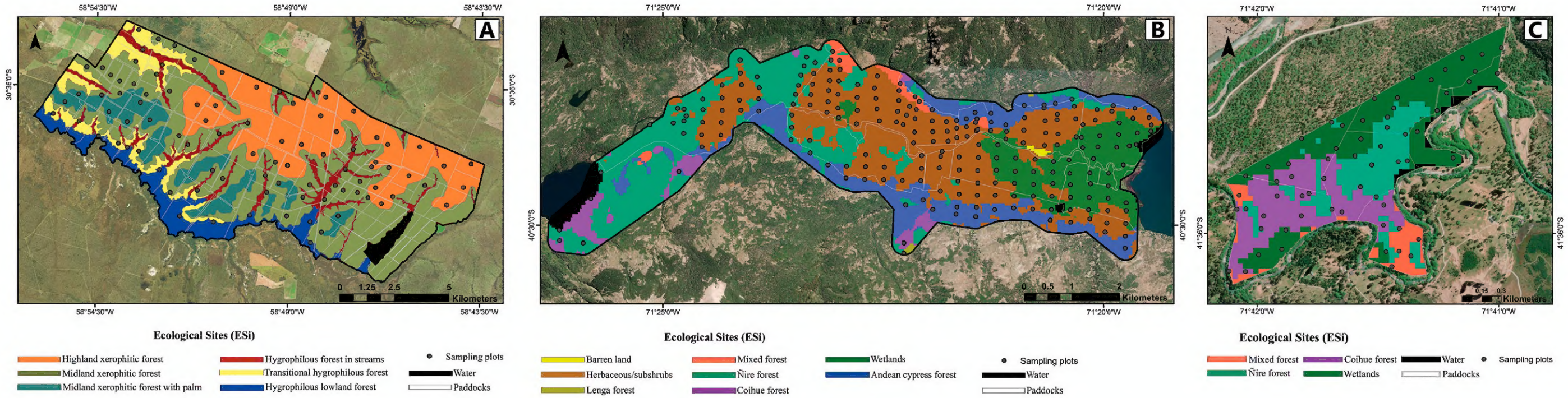

Figure 2. Spatial distribution of the Ecological Sites (ESi), Water bodies and Sampling points (plots) and Paddocks on each ranch: A) El Carayá (Entre Ríos); B) Tres Lagos (Neuquén), and C) El Jabalí (Rio Negro). Different colors indicate the different ESi.

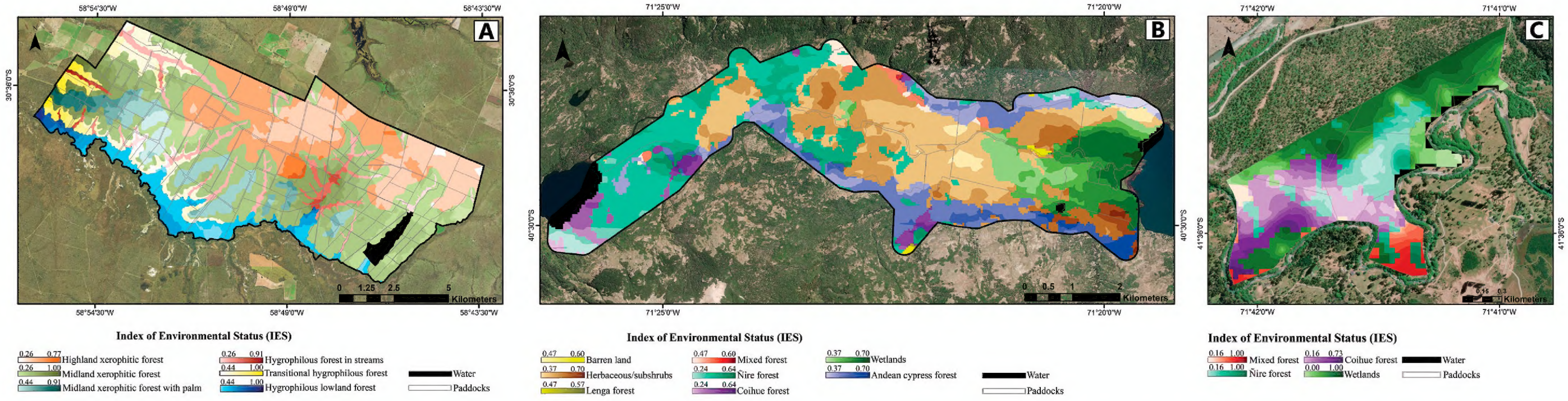

Figure 3. Spatial distribution of the Environmental Health Index (EHI) values within each Ecological Site (ESi) on each ranch: A) El Carayá (Entre Ríos); B) Tres Lagos (Neuquén), and C) El Jabalí (Rio Negro). Low EHI values (lighter colors) indicate "worse" environmental status/higher degradation within each ESi.

Table 1. Descriptive statistics of the Environmental Health Index (EHI) on each ranch. SD = standard deviation.

Ecological Site (ESi)	Mean	SD	Range of EHI		Area EHI	
					ha	%
El Carayá						
Highland xerophytic forests	0.57	0.21	0.26	0.44	33	1.03
			0.44	0.57	1431.81	44.52
			0.57	0.67	1633.99	50.80
			0.67	0.73	98.33	3.06
			0.73	0.77	19.24	0.60
Midland xerophytic forests	0.71	0.18	0.26	0.44	45.98	0.92
			0.44	0.57	949.13	18.91
			0.57	0.67	2701.51	53.83
			0.67	0.73	722.31	14.39
			0.73	0.77	391.98	7.81
			0.77	0.80	139.99	2.79
			0.80	0.85	39.7	0.79
			0.85	0.91	28.06	0.56
			0.91	1.00	0.24	0
Midland xerophytic forest with palms	0.64	0.23	0.44	0.57	179.72	15.50
			0.57	0.67	558.64	48.17
			0.67	0.73	204.47	17.63
			0.73	0.77	82.53	7.12
			0.77	0.80	97.98	8.45
			0.8	0.85	30.84	2.66
			0.85	0.91	5.52	0.48
Hygrophilous forests in streams	0.54	0.18	0.44	0.57	93.88	11.39
			0.57	0.67	447.66	54.29
			0.67	0.73	99.49	12.07
			0.73	0.77	103.14	12.51
			0.77	0.8	60.14	7.29
			0.80	0.85	16.09	1.95
			0.85	0.91	4.12	0.50
Transition hygrophilous forests	0.74	0.15	0.44	0.57	79.43	8.24
			0.57	0.67	524.58	54.41
			0.67	0.73	124.12	12.87
			0.73	0.77	29.05	3.01
			0.77	0.80	65.27	6.77
			0.80	0.85	86.64	8.99
			0.85	0.91	48.71	5.05
			0.91	1.00	6.34	0.66
Hygrophilous lowland forest	0.56	0.16	0.44	0.57	69.39	7.37
			0.57	0.67	567.59	60.32
			0.67	0.73	191.78	20.38
			0.73	0.77	40.91	4.35
			0.77	0.80	45.57	4.84
			0.80	0.85	13.19	1.40
			0.85	0.91	12.29	1.31
			0.91	1.00	0.30	0.03
Tres Lagos						
Barren land	0.54	0.03	0.47	0.53	0.0007	0.01
			0.53	0.57	5.25	96.67
			0.57	0.6	0.18	3.31
Herbaceous/ subshrubs	0.55	0.07	0.37	0.47	43.68	4.07
			0.47	0.53	496.43	46.24
			0.43	0.57	407.39	37.95
			0.57	0.6	87.73	8.17
			0.6	0.64	33.19	3.09
			0.64	0.7	5.13	0.48
Nothofagus pumilio forest	0.52	0.03	0.47	0.53	3.94	77.87
			0.53	0.57	1.12	22.13
Mixed forest	0.54	0.03	0.47	0.53	27.65	47.74
			0.53	0.57	29.08	50.21
			0.57	0.6	1.19	2.05
Nothofagus antarctica forest	0.49	0.1	0.24	0.37	23.39	3.26
			0.37	0.47	41.31	5.75
			0.47	0.53	407.49	56.76
			0.43	0.57	224.33	31.25
			0.57	0.6	21.4	2.98
			0.6	0.64	0.03	0
Nothofagus dombeyi forest	0.49	0.1	0.24	0.37	9.82	8.84
			0.37	0.47	15.29	13.76
			0.47	0.53	32.24	29.01
			0.43	0.57	37.75	33.97
			0.57	0.6	15.65	14.08
			0.6	0.64	0.39	0.35
Wetlands	0.55	0.08	0.37	0.47	1.27	0.29
			0.47	0.53	116.61	26.37
			0.43	0.57	91.39	20.67
			0.57	0.60	104.54	23.64
			0.60	0.64	120.67	27.29
			0.64	0.70	7.71	1.74
Andean cypress forest	0.55	0.08	0.37	0.47	26.91	5.33
			0.47	0.53	136.81	27.1
			0.43	0.57	251.91	49.9
			0.57	0.60	57.61	11.41
			0.60	0.64	31.48	6.24
			0.64	0.70	0.07	0.01
El Jabalí						
Mixed forest	0.45	0.19	0.16	0.26	2.03	17.59
			0.26	0.32	0.2	1.73
			0.32	0.35	0.15	1.3
			0.35	0.37	0.39	3.38
			0.37	0.41	1	8.67
			0.41	0.47	1.66	14.38
			0.47	0.57	1.85	16.03
			0.57	0.73	2.1	18.2
			0.73	1.00	2.16	18.72
Nothofagus antarctica forest	0.45	0.19	0.16	0.26	5.89	15.92
			0.26	0.32	14.15	38.25
			0.32	0.35	6.86	18.55
			0.35	0.37	2.45	6.62
			0.37	0.41	2.79	7.54
			0.41	0.47	2.11	5.7
			0.47	0.57	0.88	2.38
			0.57	0.73	0.98	2.65
			0.73	1.00	0.88	2.38
Nothofagus dombeyi forest	0.4	0.13	0.16	0.26	8.47	19.09
			0.26	0.32	12.69	28.6
			0.32	0.35	7.17	16.16
			0.35	0.37	3.28	7.39
			0.37	0.41	3.87	8.72
			0.41	0.47	5.49	12.37
			0.47	0.57	2.56	5.77
			0.57	0.73	0.84	1.89
Wetlands	0.42	0.21	0.00	0.16	0.32	0.45
			0.16	0.26	2.91	4.08
			0.26	0.32	5.42	7.6
			0.32	0.35	5.66	7.94
			0.35	0.37	3.08	4.32
			0.37	0.41	7.06	9.91
			0.41	0.47	15.84	22.23
			0.47	0.57	21.41	30.04
			0.57	0.73	9.00	12.63
			0.73	1.00	0.57	0.8

Table 2. Percentage of sampling plots (%) for each value of variables surveyed in the field for each ranch. The range of values for each variable is explained in the previous table (Suppl. material 1). Total number of sampling plots/ranch: El Carayá = 92, El Jabalí = 63, Tres Lagos = 227. N/A= Does not apply.

El Carayá

Indicator	Species	Percentage of sampling plots (%)					Indicators grouping
		0	**1**	**2**	**3**	**4**	
Soil hydric erosion		89	1	7	3	0	Soil
Physical crust		69	11	20	0	0	
Litter cover		10	50	20	20	0	
Herbaceous cover		0	16	41	43	0	Vegetation
Estimated tree density		0	2	17	48	33	
Predominant tree height		0	25	62	13	-	
Tree mortality/dead trees		20	63	16	1	0	
Shrub cover		9	68	16	7	0	
Indicator species (see in the text)	*Baccharis* spp.	66	34	-	-	-	
	Aloysia gratissima	20	80	-	-	-	
	Neltuma affinis	13	87	-	-	-	
	Neltuma nigra	53	47	-	-	-	
	Aspidosperma quebracho-blanco	84	16	-	-	-	
	Psidium guajava	48	52	-	-	-	
	Butia yatay	97	3	-	-	-	
	Trithrinax campestris	53	47	-	-	-	
Relative regeneration /abundance of native tree renewal		0	20	43	37	0	
Fire		94	3	3	0	0	Threats/ degradation processes
Flooding		45	35	10	10	0	
Invasive exotic tees		98	2	-	-	-	
Invasive herbaceous/shrub species	*Eryngium paniculatum*	51	41	4	4	0	
	Melica macra	63	29	4	4	0	
Overgrazing signs		30	25	25	20	-	

Tres Lagos

Indicator	Species	Percentage of sampling plots (%)						Indicators grouping
		N/A	**0**	**0.25**	**0.5**	**0.75**	**1**	
Soil hydric erosion		0	22	8	17	33	20	Soil
Volcano ash accumulation		0	37	4	6	49	4	
Loss of vegetal cover		0	29	7	9	33	22	Vegetation
Herbaceous cover		11	5	0	15	13	56	
Upper canopy cover		11	19	0	16	29	25	
Tree mortality/dead trees		0	82	6	5	6	1	
Shrub encroachment		0	63	6	11	17	3	
Indicator species (see in the text)	*Acaena splendens*	0	45	0	0	0	55	
	Berberis spp.	0	48	0	0	0	52	
	Chusquea culeou	0	1	0	0	0	99	
	Rubus ulmifolius	0	100	0	0	0	0	
	Rosa eglanteria	0	96	0	0	0	4	
Dead woody material		0	82	4	5	9	0	
Relative regeneration/abundance of native tree renewal		96	4	0	0	0	0	
Invasive exotic fauna	Ovines	0	100	0	0	0	0	Threats/ degradation processes
	Rabbit	0	33	17	26	18	6	
	Hares	0	85	10	4	1	0	
	Deers	0	11	23	42	20	4	
	Wild boar	0	92	3	4	0	1	
	Equines	0	42	26	0	28	4	
	Bovines	0	30	23	0	32	15	
Invasive herbaceous/shrub species		0	93	2	3	1	1	
Browsing signs		0	78	4	5	11	2	

El Jabalí								
Indicator	**Species**	**Percentage of sampling plots (%)**						**Indicators grouping**
		N/A	**0**	**0.25**	**0.5**	**0.75**	**1**	
Soil hydric erosion		0	44	14	32	10	0	Soil
Volcano ash accumulation		0	100	0	0	0	0	
Loss of vegetal cover		0	62	6	22	10	0	Vegetation
Herbaceous cover		35	63	0	2	0	0	
Upper canopy cover		3	43	0	8	29	17	
Tree mortality/dead trees		0	79	17	3	0	0	
Shrub encroachment		0	25	2	29	41	3	
Indicator species (see in the text)	*Acaena splendens*	0	94	0	0	0	6	
	Berberis spp.	0	51	0	0	0	49	
	Chusquea culeou	0	52	0	0	0	48	
	Rubus ulmifolius	0	24	0	0	0	76	
	Rosa eglanteria	0	13	0	0	0	87	
Dead woody material		0	68	19	10	3	0	
Relative regeneration/abundance of native tree renewal		60	21	0	2	8	10	
Invasive exotic fauna	Ovines	0	81	6	10	3	0	Threats/ degradation processes
	Rabbit	0	97	0	3	0	0	
	Hares	0	100	0	0	0	0	
	Deers	0	100	0	0	0	0	
	Wild boar	0	78	8	11	3	0	
	Equines	0	56	19	0	16	10	
	Bovines	0	22	13	0	52	13	
Invasive herbaceous/shrub species		0	21	5	29	43	3	
Browsing signs		0	35	2	17	44	0	

processes or threats. In this way, our methodological approach builds upon and advances previous studies that combined remote sensing with field data for ecological assessments (e.g., Kerr and Ostrovsky 2003; del Río Mena et al. 2020; Xia et al. 2024). A key contribution of this study is the novel combination of ESi delineation (based on remote sensing) and RAM (based on field data), applied to South American livestock ranches located in highly contrasting ecoregions, such as Patagonia (sub-humid forests) and the Espinal (xerophytic woodlands).

A total of six, eight, and four ecological sites (ESi) were identified in El Carayá, Tres Lagos, and El Jabalí, respectively. This highlights the utility of the approach for distinguishing homogeneous units based on vegetation and abiotic characteristics at the ranch scale, even in highly contrasting environments. In El Carayá, no previous studies have explicitly applied the ESi framework. However, the six ESi identified through the methodological approach used in this study largely coincided with previously defined homogeneous environmental units based on vegetation, topography, and/or soil (Sabattini et al. 2015 – soil map and Landsat images; Reales et al. 2021 – visual interpretation of Google Earth imagery). Nevertheless, the approach used here provides a more detailed and accurate description of environmental units, as it establishes a gradient of environmental condition within each mapped unit, based on the EHI (estimated from the RAM). Additionally, it increases the spatial analysis scale, shifting from 1:100,000 (Sabattini et al. 2015) to 1:20,000 (this study).

The same occurred in the two Patagonian ranches where, to our knowledge, this study represents the first attempt to identify and characterize ESi within forest ecosystems. The resulting classifications were consistent with existing forest typologies (CIEFAP-MAyDS 2016; Mohr Bell et al. 2019), which have evolved conceptually over time and incorporated field-based data. Although earlier work has delineated potential ecological sites and reference states for specific forest types (e.g., *Nothofagus dombeyi - Austrocedrus chilensis* mixed forests, Rush et al. 2016, *Nothofagus antarctica* forests, Rusch et al. 2017; Peri et al. 2022), there has been a lack of methodological frameworks integrating environmental unit delineation with rapid, field-based assessments of current degradation processes. Our approach addresses this gap and provides a valuable tool (RAM) to support more refined environmental sampling (e.g., forest inventories) and inform management decisions aimed at reversing degradation processes.

The RAM developed and implemented in this study, facilitated the identification of areas requiring more intensive intervention within ranches, based on the current environmental status of each ESi. In sites where prior information was available regarding vegetation types or degradation levels (e.g., Sabattini et al. 2015; Reales et al. 2021 for El Carayá Ranch), RAM provided a finer understanding of degradation processes, such as overgrazing and shrub encroachment. It is worth noting that the indicators evaluated in El Carayá were partially based on the quali-quantitative variables proposed by Casermeiro and Spahn (2000) to characterize native forest status in Entre Ríos. However, this study went beyond that type of characterization by integrating the indicators recorded through RAM into an Environmental Health Index (EHI), which was estimated and standardized using statistical methods. This integration provided a spatially explicit proxy for ecosystem status.

Finally, the EHI values estimated in this study revealed that intermediate levels of environmental health

predominated across the studied ranches. For instance, in El Carayá and Tres Lagos, approximately 95% of the area exhibited EHI values ranging from 0.4 to 0.73, while El Jabalí showed a greater proportion of forested areas with intermediate to low EHI values (EHI < 0.58). These results revealed a spatial gradient of degradation across forest and pastoral ecosystems within each ranch, consistent with previous findings for the Patagonia and Espinal ecoregions, where long-term livestock grazing, forestry production, and frequent fires have been documented (Sabattini et al. 1999; Sabattini and Sabattini 2019; Rusch and Varela 2019; De Marzo et al. 2021; Peri et al. 2021).

Despite this history of anthropogenic pressure in Patagonia and Espinal ecoregions (Sabattini et al. 1999; Rusch and Varela 2019; Sabattini and Sabattini 2019), the predominance of intermediate EHI values suggests a certain degree of resilience in these ecosystems, potentially linked to the resprouting and regeneration capacity of native vegetation (Brown et al. 2006; Peri et al. 2021). Notably, El Jabalí Ranch exhibited the lowest overall environmental health values, which may reflect the high pressure resulting from livestock–forestry practices adopted by small-scale ranchers. This interpretation is supported by complementary assessments (S. Varela, pers. obs.), which reported high stocking rates and visible signs of overgrazing in this ranch—findings that are consistent with the information derived from RAM indicators and their integration into the EHI.

Furthermore, the mapping of EHI proved to be accurate, as indicated by a mean squared error of the spatially explicit EHI models close to zero, across a wide range of ranch sizes—from very small (<100 ha) to large ranches (>10,000 ha). Importantly, the consistency of the method suggests strong potential for application at broader spatial scales. Scaling up to the landscape level, as proposed in previous studies (Pettorelli et al. 2014; Ireland and Drohan 2014; Maynard and Karl 2017), could enhance its utility for regional land-use planning and conservation strategies, while also helping to bridge the scale mismatch between traditional field-based ecological data and remote sensing data (Kerr and Ostrovsky 2003).

Nevertheless, it is important to acknowledge some limitations of these tools. In the case of ESi identification, the ESi viewer developed and applied to Patagonian ranches is still under development and will undergo continuous refinement to improve the accuracy of its classifications. In addition, the classification of meadows was based on a country-level meadow probability map (Navarro et al. 2022), which may require field validation to determine the precise extent of meadow areas. We expect that future implementations and updates of this tool will contribute to increasing the precision of ESi maps.

In the case of RAM, although it provides a valuable rapid assessment tool, it may not capture the full range of environmental degradation or the complexity of ecological systems, potentially limiting the depth of information obtained (Fennessy et al. 2007). The lower investment in human and economic resources—due to reduced field effort compared to more intensive sampling—makes this approach particularly appealing for scaling up to the regional level, enabling more targeted and efficient sampling beyond the ranch (local) scale (Fennessy et al. 2007). Additionally, similar rapid evaluation methods have previously been applied in forest ecosystems, showing very good performance (Davis et al. 2016). However, the trade-off between speed and detail is a well-known constraint and frequent criticism of rapid assessment methodologies (Sayre et al. 2000). Future analyses should compare the methodology proposed in this study with existing guidelines for more in-depth assessment of environmental indicators (Carranza et al. 2019; Peri et al. 2021), to evaluate the precision and cost-effectiveness of each approach.

Additionally, future research could address these limitations by exploring methods to improve the depth and accuracy of RAM. For instance, combining RAM with more detailed assessment techniques to evaluate quantitative indicators of forest health -such as regeneration stages, tree density, and soil condition- could enhance precision and help reduce observer bias. Similarly, incorporating expert knowledge and empirical data to assign relative weights to multiple variables within the EHI framework could improve its sensitivity and accuracy, ultimately leading to more informed land management decisions. In this way, we aim to foster a more comprehensive understanding of ecosystem health and resilience, contributing to more effective and adaptive management practices at the ranch scale.

Considering that all terrestrial ecosystems in the world, including Argentina, are subject to some level of human use, spatial monitoring of landscape ecological health is crucial. In this sense, the EHI proposal makes a novel and key contribution to spatial monitoring and adaptive management of terrestrial ecosystems. Remote sensing data and techniques address the requirement of ecological evaluations at broad spatial extents that cannot be collected using field-based methods (Kerr and Ostrovsky 2003). This includes identifying and detailing the biophysical characteristics of species habitats, predicting the distribution of species and spatial variability in species richness, and detecting natural and human-caused changes at scales ranging from individual landscapes to the entire world (Kerr and Ostrovsky 2003). This consistency supports the utility of integrated methods for assessing environmental health and landscape-level variability, particularly in complex and heterogeneous ecosystems.

Implementing a monitoring system based on ESi, RAM, and the EHI potentially would enable ranchers to track ecosystem responses to management interventions more easily than with more intensive and expensive field sampling, such as the one proposed in current guidelines to evaluate environmental indicators in forests with livestock production (Carranza et al. 2019; Peri et al. 2021). These tools (ESi, RAM, and EHI) are especially beneficial for monitoring extensive and inaccessible terrains, particularly in complex and heterogeneous silvopastoral systems. The capacity to monitor diverse environments and

soil types facilitates critical assessments for adaptive management, ultimately promoting improvements in ranchers' livelihoods while conserving and/or restoring local ecosystems (Peri et al. 2021, 2022).

We expect that the approach presented in this study will help align livestock management practices with efforts to maintain or improve forest quantity and quality, both in Argentina and in other countries where native forests are used for livestock production. In particular, the EHI developed here offers a promising tool for monitoring changes in forest status and informing adaptive management decisions aimed at minimizing negative impacts while fostering ecosystem recovery and resilience. As land-use pressures continue to rise, integrating tools such as ESi, RAM, and EHI into broader management frameworks will be essential for achieving long-term sustainability in forested ecosystems. In doing so, they support global discussions and initiatives aimed at maintaining forest multifunctionality within sustainable land management frameworks (UNEP 2021; FAO 2022; IPCC 2023).

Data availability

Data used in the present manuscript will be made available upon request.

Author contributions

SAV, NCC and SBC planned the research, study conception and design, conducted the field sampling, performed the analyses and interpretation of results and led the writing. FDT conducted the analysis of Ecological Sites and reviewed the early draft version. JPD, MW, FRB, LL, RPC and RDC conducted the field sampling, collected data and critically revised the early draft version for important intellectual content. DRL, PLP and HH supervised the study and reviewed the early draft version. FJU; FR; JIG; CDP; MW and EG conducted the draft manuscript preparation. The authors agreed to be accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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Supplementary material

Supplementary material 1
List of indicator variables included in the estimation of the Index of the Environmental Health Index (EHI) and its consideration within Indicator grouping on each ranch and the considered value/range (*.pdf)
Link: https://doi.org/10.3897/VCS.141917.suppl1

Supplementary material 2
Comparative errors of the ordinary kriging semi variogram models and model parameters tested per ranch (*.pdf)
Link: https://doi.org/10.3897/VCS.141917.suppl2

Supplementary material 3
Observed and predicted values, along with errors, for 30% of the dataset used to validate the selected interpolation model for each study ranch (*.pdf)
Link: https://doi.org/10.3897/VCS.141917.suppl3